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COST OPTIMIZATION OF USING GEOGRIDS VS PILES IN THE FOUNDATION OF INTERCHANGE BRIDGES

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ABSTRACT

The use of soil reinforcement has become widely adopted due to successive development of different types of geosynthetics. Although soil reinforcement had gained wide acceptance in other countries, Iraq is still hesitated to adopt the system. This paper is an economic study to investigate the feasibility of using geogrids in the foundation of interchange bridges, resting on sandy soils, instead of piles. The design restrictions are imposed as design constraints in the analysis of both cases (geogrids and piles). Choice of the design parameters are made in a way that fit local circumstances in middle and south Iraq considering common safety factors. Three layers of two types of geogrids are analyzed namely Netlon CE121 and Tensar SS2. MATLAB package program is used for optimization. The constraints and the objective function are designed to optimize one unit block of foundation (under one piles cap). Tables of optimal costs and figures showing cost behavior for different combinations of loads and angles of internal friction of soil are presented. It has been found that reinforced soil is considered as cost-effective solution which is much more economical than piles. Based on a typical design commonly used on local scale, cost saving appear to reach (54%).

Keywords: Bearing Capacity, Geosynthetics, Netlon CE121 and Tensar SS2 Geogrids, Optimal Cost Design, Optimization, Sandy Soil.

1. INTRODUCTION

This paper is an economic study of using geogrids in the foundation of highway multi-level intersection bridges instead of piles. The study is limited to the range of applied loads prevailing in most of highway projects in middle and south Iraq and the bearing capacity of reinforced soil of the most common type founded in the aforementioned area where most of the soil is sand. MATLAB is used as an optimization technique in order to find the optimum cost of construction of both types of

foundations (reinforced soil and piles). Comparison between the two cases is adopted to decide whether the use of geogrids is more economic than the use of piles within the range of applied loads. The cost of construction is estimated according to the prevailing local prices at the time of this study.

1.1 Research Objectives

The objective of this study is to investigate the feasibility of using geogrids in the foundation of highway multi-level intersection bridges resting on sandy soil instead of piles.

1.2 Research Justification

Although accomplishing high quality construction projects with minimum cost and time is everybody's goal, an additional need to substitute piles with soil reinforcement arise when some underground structures like subways undercrosss the location of work where no piles can be installed.

1.3 Research Hypothesis

The bearing capacity of the soil can be highly improved by reinforcing it with geogrids, so it can bear the applied load resulted from dead and live loads of the bridge, without any need to use costly piles.

2. DESIGN CONSIDERATIONS

Design drawings and calculations of thirty multi–level intersection bridges in Al-Najaf, Karbala, and surrounding are reviewed in order to determine the range of the most common applied loads, the number of piles per cap, the number of piers on each cap, and dimensions. A representative sample of typical design related to the bridge of Northern Garage in Al-Najaf City is adopted as a case study. Review of drawings and calculations reveals that the applied load on each pier is within (10386 kN). The pile cap is considered to be rigid having four piles with pile diameter of (1.5 m) and pile length of (18 m) according to the typical design. This means that the total applied load on the pile cap is (41544 kN). On the other hand the analysis covers the case of using geogrids instead of piles for the same area of interaction as shown in Fig. (1). Two types of geogrids are put into consideration, namely Netlon CE121 and Tensar SS2. According to previous research conducted by the same authors, three layers of geogrids at a depth equal to the width of the footing (B) and a distance of (3.6B) from the centerline of footing in both directions is found to be adequate [1][2].

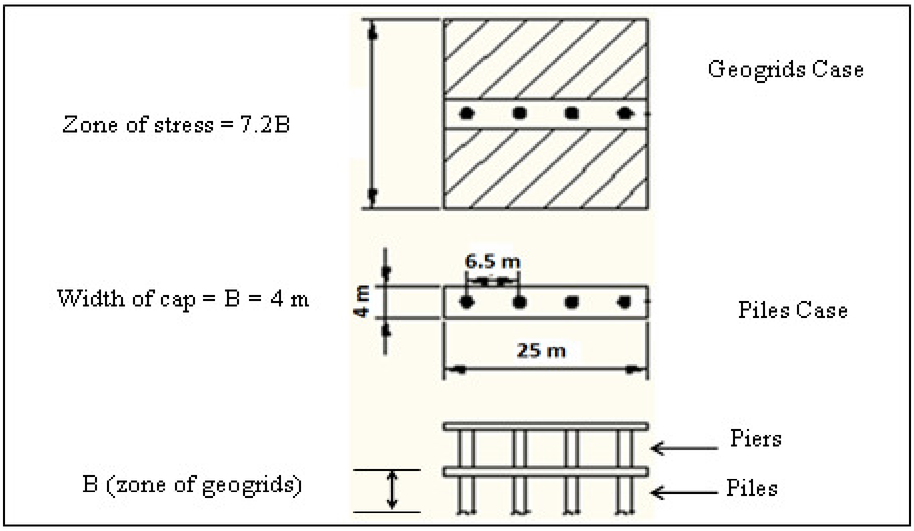

Figure 1: One design unit for the sake of cost comparison

3. OBJECTIVE FUNCTION OF THE REINFORCED SOIL CASE

As shown in Fig. (1), the zone of interaction in this case have the dimensions of (7.2B × L × h), where dimensions are in meters and (h = B) according to [1] [2]. The objective function is formulated to yield the optimum size of footing and its cost in IQD (Iraqi Dinars) according to the following input parameters; total load on footing (P), unit weight of existing natural soil (γ_s), angle of internal friction of existing natural soil (Ø), cost of geogrids (cg) in (IQD/m^2), cost of excavation (ce) in (IQD/m^3), cost of filling and compaction (cf) in (IQD/m^3), cost of other work items including laying of geogrids (cw) in (IQD/m^2) for each layer, and safety factor (SF). The cost of the concrete footing itself is excluded because it is the same in both cases (reinforced soil and piles). The objective function is expressed in MATLAB as follows:

F = nl*cg*sz*x(1)*x(2) + ef*ce*x(1)^2*x(2) + nl*cw*sz*x(1)*x(2) + ef*sz*cf*x(1)^2*x(2) (1)

where,

x(1): width of footing in meters (B) or depth of the end layer of geogrids in meters for (h = B).
x(2): L: length of footing in meters.
nl: number of geogrids layers (three).
sz: stress zone on both sides of the footing (7.2B).
ef: expansion factor for excavation and filling.

4. CONSTRAINTS OF THE REINFORCED SOIL CASE

The constraints include both types of failure that design should account for, soil failure and geogrids structural failure. Soil failure must meet both main criteria of bearing capacity and settlement limitation. Structural failure must meet shear and flexural strength of geogrids. Constraints are formulated as follows:

4.1 Bearing Capacity Constraint of the Reinforced Soil Case

The allowable soil pressure must be greater than or equal to the maximum applied pressure ($q_{all} \geq q_{max}$) or ($q_{ult}/SF \geq q_{max}$). The ultimate bearing capacity (q_{ult}) can be calculated using Hansen's equation as follows [3]:

$$\mathbf{q_{ult} = cN_c s_c d_c + qN_q d_q + 0.5\gamma_s B N_\gamma s_\gamma d_\gamma} \quad (2)$$

For the footing resting on the surface of sand (c = 0), the equation of bearing capacity will be:

$$\mathbf{q_{ult} = 0.5\gamma_s B N_\gamma s_\gamma d_\gamma} \quad (3)$$

where:

$$\mathbf{N_q = e^{\pi \tan Ø} \tan^2(45+Ø/2)} \quad (4)$$

$$\mathbf{N_\gamma = 1.5(N_q-1) \tan Ø} \quad (5)$$

$$\mathbf{s_\gamma = 1-0.4\, B/L} \quad (6)$$

$$\mathbf{d_\gamma = 1}$$

The maximum applied pressure is calculated by the basic principle of (q_{max} = P/BL) and (q_{all} = q_{ult}/SF). The value of bearing capacity of sand must be multiplied with BCR value of (1.88) for Netlon CE121 and (2.5) for Tensar SS2 [1][2]. Therefore the bearing capacity constraint is written in MATLAB as:

g1 =-0.5*gama*x(1)*(1.5*(Nq-1)*tan(fai*pi/180))*(1-0.4*x(1)/x(2))*BCR*x(1)*x(2) + SF*P (7)

where,
gama: unit weight of sand (16.7 kN/m^3).
fai: angle of internal friction of soil
pi: π.
BCR: bearing capacity ratio of reinforced to unreinforced sand.
SF: safety factor.
P: total axial load.

4.2 Settlement Constraint of the Reinforced Soil Case

To satisfy that immediate settlement (s_i) of the footing does not exceed a permissible limit, the subgrade reaction equation is used [3]:

$$\mathbf{s_i = w_t/k_s = (P/BL)/k_s} \tag{8}$$

where (k_s) is the modulus of subgrade reaction (kN/m^3) calculated by (k_s = 120*q_{all}) or (k_s =120*q_{ult}/SF) [3].

The permissible (s_i) is decided to be (0.025m), so,

$$\mathbf{3*q_{ult} = P/BL} \tag{9}$$

Thus, the constraint can be written in MATLAB as:

g2 = 3*(0.5*gama*x(1)*(1.5*(Nq-1)*tan(fai*pi/180))*(1-0.4*x(1)/x(2))*BCR*x(1)*x(2) + SF*P (10)

The dimensions of footing must enclose all the piers on the pile cap, therefore the lower limits of (x_i) i.e. (L&B) are pre-fed into the optimization tool box of MATLAB according to the dimensions of the pile cap.

5. OPTIMIZATION RESULTS OF THE REINFORCED SOIL CASE

After running the program, the optimum dimensions (B and L) and the minimum construction cost of the reinforced soil under the zone of one row of piers is obtained. Table (1) shows the optimum cost and dimensions determined by the program that make the reinforced soil under footing safe in sense of bearing capacity and allowable settlement to bear the applied load from the super-structure of the bridge.

Table 1: Inputs and outputs of cost optimization analyses of the reinforced soil case

Inputs			Outputs		
item	unit	value	item	unit	value
P	kN	41544	B	m	4
Geogrids layers	No.	3			
BCR	For Netlon	1.88			
	For Tensar	2.5	L	m	25
(cost of geogrid), cg	IQD/m^2	10000.000			
(cost of excavation), ce	IQD/m^3	1000.000			
(cost of work), cw	IQD/m^2	2000.000	Cost	IQD/row	29,856,000.000
(cost of filling and compaction), cf	IQD/m^3	1000.000			
(unit weight of soil), γs	kN/m^3	16.7			
(Plane strain angle of internal friction), Ø°	degrees	43			
(safety factor), SF	---	2			

6. OBJECTIVE FUNCTION OF THE PILES CASE

In this case, one row of piles as shown in Fig. (1) is put into consideration. The construction cost of piles includes three items; cost of concrete (cc) in (IQD/m^3), cost of steel reinforcement (cs) in (IQD/ton), and cost of work (cwp) in (IQD/m) for (D_p = 1 to 1.5m). The cost of the piles cap is excluded as in the case of reinforced soil. Other input parameters are; total load on footing (Pp), unit weight of soil (γ_s), angle of internal friction (Ø), and safety factor (SF). The objective function is formulated to yield the optimum size of pile including diameter (D_p) and length (L_p) in meters and its cost for one row of piles according to the aforementioned variables which is expressed in MATLAB as:

F = np*cwp*x(2) + np*cc*pi/4*(x(1))^2*x(2) + 0.01*7.8*np*cs*pi/4*(x(1))^2*x(2) (11)

where, x(1) = D_p, x(2) = L_p, γ_{steel} = 7.8 ton/m^3, (np) is the number of piles, and the minimum steel area is equal to (ρ_{min} × cross sectional area of pile) where (ρ_{min} = 0.01) [3].

7. CONSTRAINTS OF THE PILES CASE

Failure due to end bearing and skin friction are taken into account in the formulation of constraints. The allowable capacity of each pile should not be less than the anticipated applied load of (10386 kN). The pile is considered a bored pile as they are constructed in the field. The ultimate capacity of a single pile is determined according to the American Petroleum Institute (API) design recommendations for axially loaded piles [4]. The (API) recommendations are based on a huge database of axial pile load tests that is continually evaluated and updated. The procedure is as follows:

$Q_{ult} = Q_b + \sum Q_s$

$Q_b \leq Q_{b\ max}$

$Q_{b\ max}$ for sand (c = 0) = (50 N_q tan Ø) A_b

$Q_{b\ max}$ for (c ≠ 0) = (c_b N_c + 50 N_q tan Ø) A_b

$$\mathbf{Q_{ult} = (c_b\, N_c + q\, N_q)\, A_b + \sum (\alpha\, c_s + \sigma_v\, k \tan \delta)\, A_s} \quad (12)$$

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For (c = 0) and one layer of soil, the formula becomes:

$$\mathbf{Q_{ult} = q\, N_q\, A_b + (\sigma_v\, k \tan\delta)\, A_s} \qquad (13)$$

where:
Q_b: end bearing capacity of pile.
Q_s: skin resistance of pile.
$q = \gamma_s \times L_p$
Nq: from Fig. (2) for Triaxial ($\varnothing = 40^o$) and ($N_q = 160$).
A_b: cross sectional area of pile.
$\sigma_v = \gamma_s \times (L_p/2)$
$k = (1\text{-}\sin\varnothing)$
$\delta = \varnothing$ (concrete contacts with soil directly)
A_s = surface area of pile.

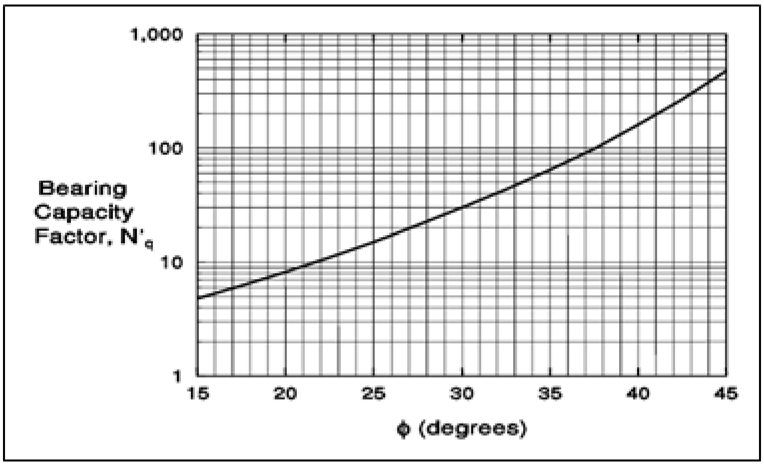

Figure 2: Chart for estimating bearing capacity factor N'q [5]

Therefore, the ultimate capacity formula of a single pile will be:

$$\mathbf{Q_{ult} = \gamma_s \times L_p \times N_q \times \pi\, (D_p)^2/4 + (\gamma_s \times (L_p/2) \times (1\text{-}\sin\varnothing) \tan\delta \times \pi \times D_p \times L_p} \qquad (14)$$

This must be multiplied by (4) to suit the case study of four piles in one row. Since the constraint is formulated to satisfy that Q_{ult} (s.p.) $\geq$ ($Q_{max} \times$ SFp), then the constraint formula is written in MATLAB as:

g1 = -1*share*np*(gama*x(2)/2*Nq*pi/4*(x(1))^2*K*(tan(fai*pi/180))*Pi*x(1)*x(2)) + Pp*SFp (15)

where,
share = 33.8% (sharing ratio of footing after [1][2]).
np = 4 (number of piles).
gama = 6.7 kN/m^3 (submerged unit weight of sand due to water table presence at 2 m depth) [6].
Nq: bearing capacity factor of pile from Fig. (2).
SFp: safety factor for piles.
Pp: total axial load on piled-strip system.

The size of pile (diameter and length) is used as in the typical design where (D_p = 1.5 m) and (L_p = 18 m). Cost is estimated according to the prevailing local prices at the time of this study. After running the program, the optimum (D_p) and (L_p) and the minimum cost of one row of piles is obtained. The optimum values of (D_p) and (L_p) required to ensure that piles are safe in sense of capacity is shown in Table (2).

Table 2: Inputs and outputs of cost optimization analyses of piles case

Inputs			Outputs		
item	unit	value	item	unit	value
Pp	kN	41544	D_p	m	1.5
(cost of work), cwp	IQD/m	500000.000			
(cost of concrete), cc	IQD/m^3	150000.000	L_p	m	18
(cost of reinforcement), cs	IQD/ton	1000000.000			
(submerged unit weight of soil), γb	kN/m^3	6.7	Cost	IQD/row	65,009,466.000
(Triaxial angle of internal friction), Ø°	degrees	40			
(safety factor), SFp	---	4			

8. PARAMETRIC ANALYSES

For the typical design adopted in this research, it is clear that the use of geogrids in the foundation of highway multi-level intersection bridges resting on sandy soil, where the angle of internal friction is higher than (40°), is more economic than piles within the limits of design loads adopted in the region. The saving in cost is found to be as much as (54%) in this case study. To have a wider generalized view, a parametric study of the optimum cost of construction is investigated using a wide range of loads and angles of internal friction of soil. Each parameter behavior is investigated through sensitivity analysis.

To study the effect of angle of internal friction on cost, a set of different values of (Ø°) (varying from 20° to 40°) is analyzed. Figures (3) and (4) show the relationship between (Ø°) and the cost of Netlon and Tensar geogrids respectively. It is clear that the cost tends towards a constant value when (Ø°) increases. For the wide range of loads analyzed (varying from 20000 kN to 60000 kN), the cost of reinforced soil by Netlon and Tensar geogrids tends towards a constant value after (Ø = 35°) and (Ø = 32°) respectively. This is because Tensar geogrid have a higher BCR than of Netlon geogrid. For the same range of loads, the cost of piles with dimensions of (D_p = 1.5 m) and (L_p = 18 m) decreases gradually after (Ø = 20°) then remain constant when the value of (Ø) exceeds (25°), as shown in Fig. (5).

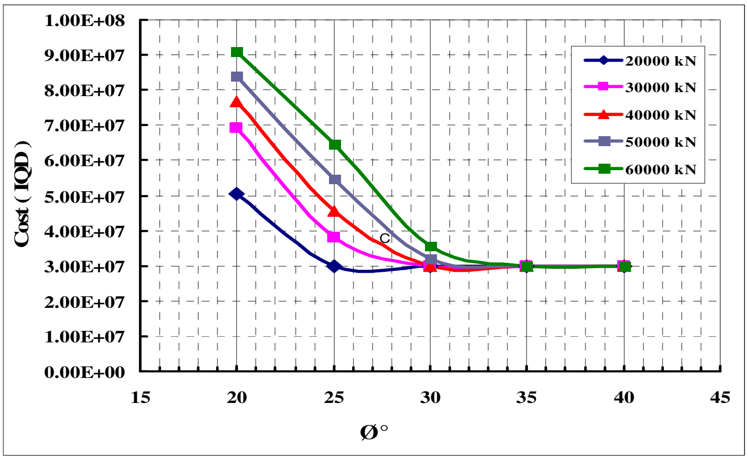

Figure 3: Relationship between Ø° and cost for Netlon geogrid

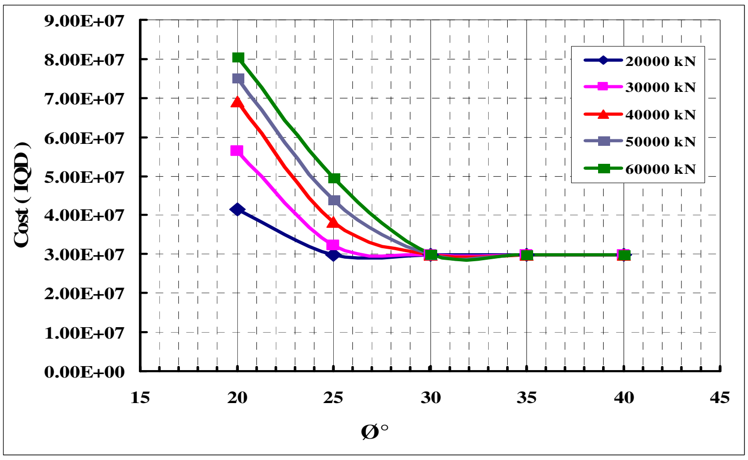

Figure 4: Relationship between Ø° and cost for Tensar geogrid

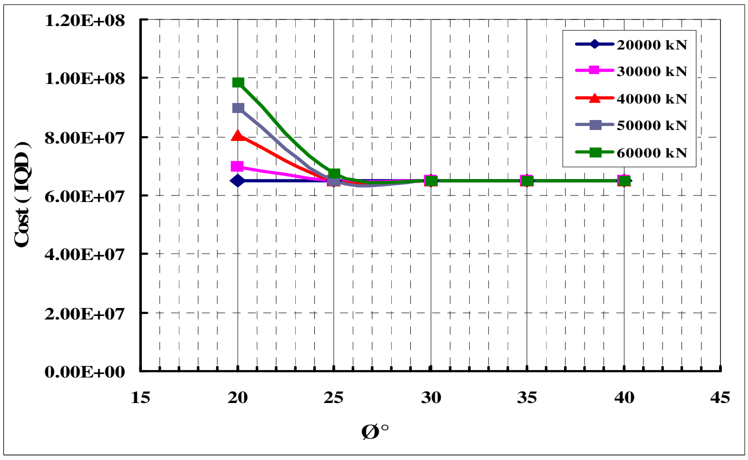

Figure 5: Relationship between Ø° and cost for piles

Figures (6), (7), (8), (9), and (10) illustrate a comparison between costs of different cases showing whether using geogrids or piles as foundations is more economic. The analyses cover relationships between load and cost for values of (Ø = 20º, 25º, 30º, 35º and 40º).

Figure (6) shows the relationship between load and cost for (Ø = 20º), where the cost increases slightly when the applied load increases for Netlon, Tensar, and piled-strip cases. Figure (7) shows the relationship between load and cost for (Ø = 25º), where the cost of the piled-strip is constant for the same range of loads because the value of (Nq) is high enough and the capacity of piles of such dimensions are sufficient to resist the adopted range of loads.

Figures (8), (9), and (10) indicate that using geogrids foundation is again more economical than piles for the load range of (20000 kN) to (60000 kN). The saving in cost increases rapidly when the value of (Ø) increases, especially when it became higher than (25º). This finding comes in line with the established knowledge that the more the fines in soil the less the effectiveness of reinforcement. Since physically, less Ø for the same relative density refers to more fines especially when it is (15%) finer than (0.075 mm) as required by AASHTO specifications and FHWA guidelines [7]. The type of geogrids does not affect the cost because of the high bearing capacity of sand, especially when the value of (Ø) is higher than (30º).

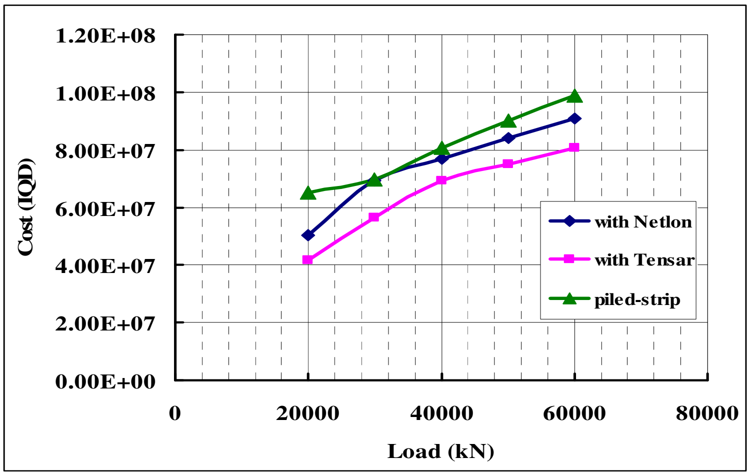

Figure 6: Relationship between load and cost for Ø = 20º

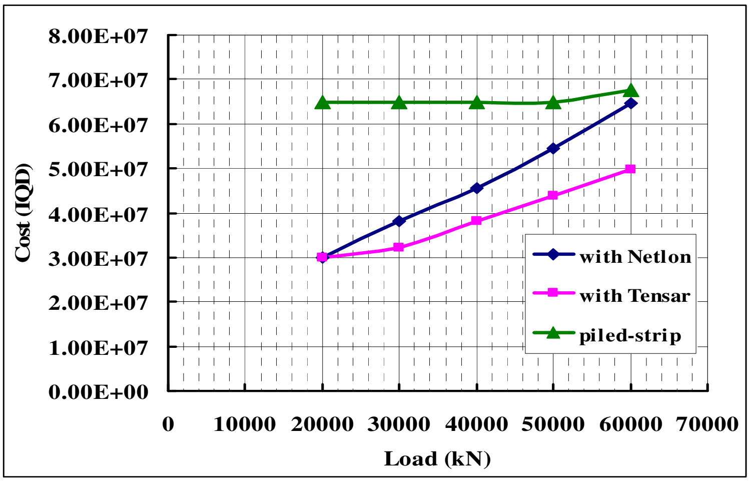

Figure 7: Relationship between load and cost for Ø = 25º

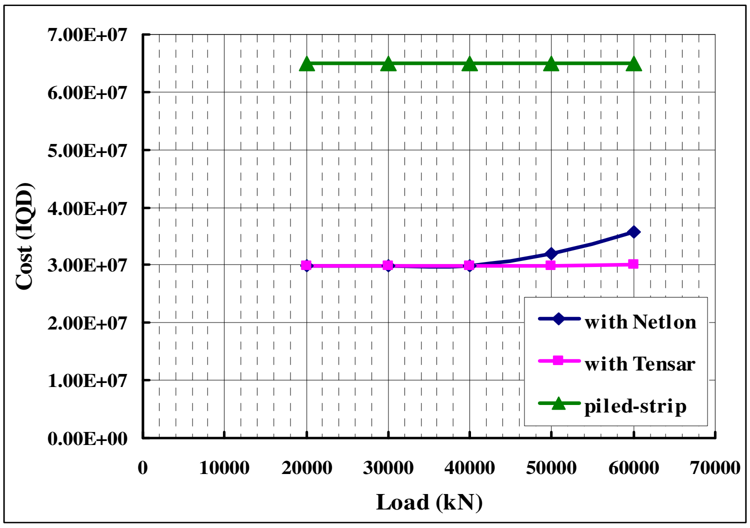

Figure 8: Relationship between load and cost for Ø = 30º

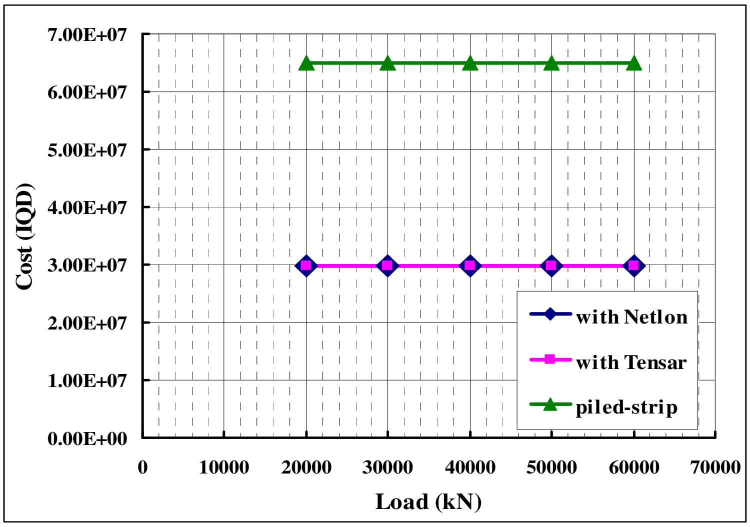

Figure 9: Relationship between load and cost for Ø = 35º

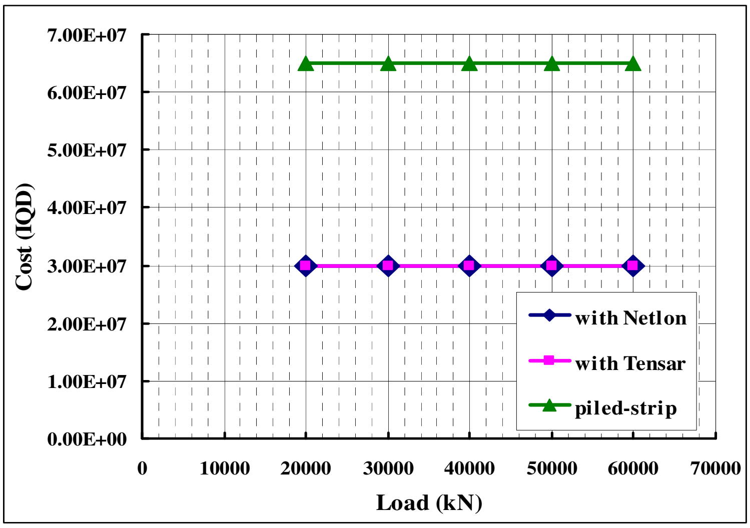

Figure 10: Relationship between load and cost for Ø = 40º

9. CONCLUSIONS AND RECOMMENDATIONS

According to the costs listed in tables (1) and (2), and the behavior of cost shown in figures (3) to (10), it can be concluded that using geogrids in the foundation of multi-level highway intersection bridges is more economic than piles within the range of applied loads, allowable bearing capacities, and settlement covered by this study. For low (Ø) values the cost, using different methods, increases with increasing loads and then becomes gradually constant for higher (Ø) values. Geogrids is highly recommended to be used instead of piles when some underground constructions or utilities undercrosss the working area.

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